# Evolvable Space Systems

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Future generations of space systems will operate for much longer time and in much harsher environments than current generation. The design of such systems will become increasingly harder. A large variety of environmental conditions may lead to contradicting requirements for different phases of the mission. The relevant information about the variety of situations that will be encountered may be imprecise, or totally lacking; thus, the space systems will need to cope with situations which were not explicitly thought of at the design phase.

A possible solution for long-life purposeful survivability, and in-situ adaptation may be the application of principles of biological evolution. We suggest here the application of evolutionary algorithms to adaptively self-reconfigure space systems for long-life purposeful survival. Evolution of Space Systems would include autonomous changes/reconfiguration of both software and hardware including sensors, avionics, and structure, etc.

In natural evolution the most fitted individuals survive becoming parents; children inherit parents' characteristics, with some variations, and may perform better, increasing the level of adaptation. In the space system, potential designs and implementations would compete; the best ones are slightly modified to search for more suitable solutions. While in nature evolution took many millions of years, the in-situ artificial evolution would be performed at a much faster pace: for electronic circuits it would be of the order of seconds.

Evolvable hardware (EHW) is a current research field that addresses the use of evolutionary algorithms (e.g. Genetic Algorithms) to obtain adaptive electronic hardware. Currently at JPL the focus of EHW research is on on-chip evolution of analog electronic circuits. This seed effort is envisaged to grow and cover other aspects of hardware adaptation, including optical, mechanical/structural and thermal characteristics.

We also suggest a technology development road map from evolvable electronics to evolvable space systems.

An important phase is considered using evolvable hardware for shaping adaptive/intelligent sensory systems, able to identify suitable exploration/observation sites/targets, and efficiently retask and adjust individual instruments, in order to provide maximal science returns for a given set of instruments and exploration environment. This would pave the road for the next phase, which would be evolution of complete space systems, capable of intelligent adaptation to unknown environments, self-healing, and long-life survivability.

# Evolvable Space Systems

For Long-Life and Inherent Survivability

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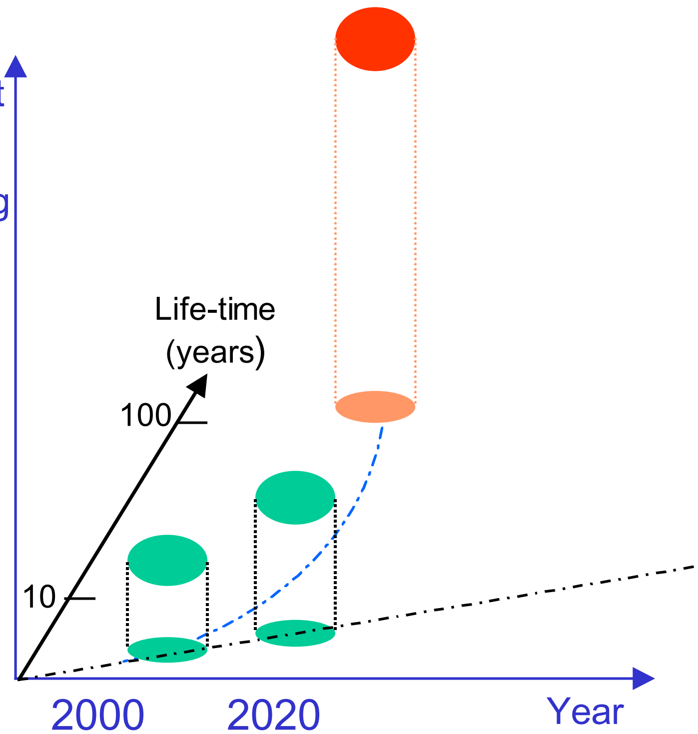
# Outline

- Long-life survivable space systems - the need for a new paradigm
- Evolvability to increase survivability
- Goal: long life purposeful survivability
- Evolutionary algorithms: inspiration, innovation, how do they work
- Evolware: from Evolvable HW to Evolvable Space Systems
- “Genetically Engineered” Devices
- A parallel implementation of an evolution machine
- Evolvable Electronics
- How would this technology revolutionize NASA Missions
- Technical Challenges
- Technology Goals

# The need for a new paradigm

Severity of
environment
- harsh
- challenging




Current space systems have a life time of few years and cope with only modestly harsh environments

Current rate of increasing life-time and survivability in new environments may be not sufficient: a novel approach is needed to speed-up

# Add evolvability to increase survivability

**Long-Life Purposeful Survivability**
•really harsh/challenging environments
•long-life (100+ years)

**Advances in**
•components
•system robustness
•space qualification
•autonomy/intelligence

+

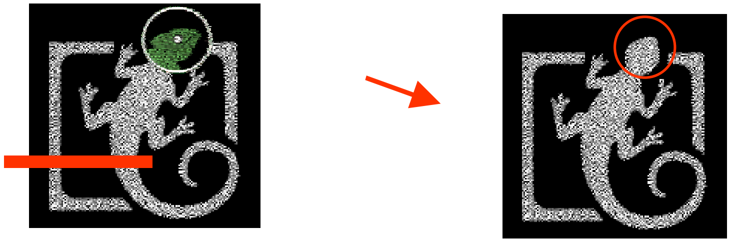
**Evolvability**
•adaptation to environments
•self-healing, self-repair

robust design from robust components

evolutionary robust design from
flexible resources:
repair, reallocation, reutilization

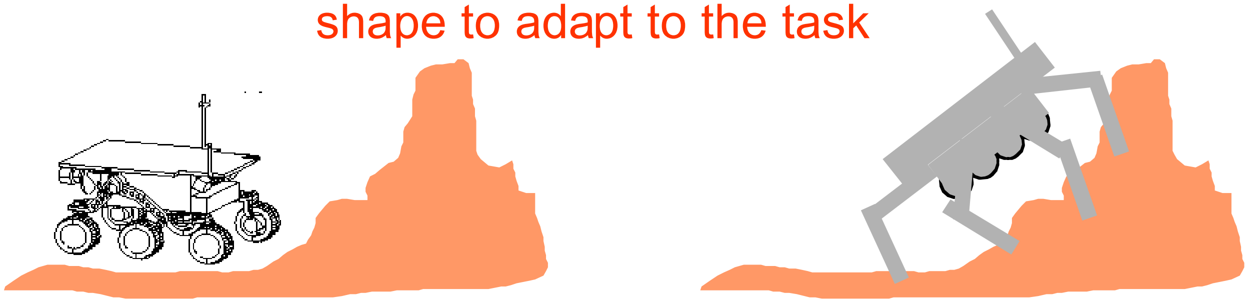
# In-situ adaptation to the task, self-healing, armadas

Chameleonic Space Systems



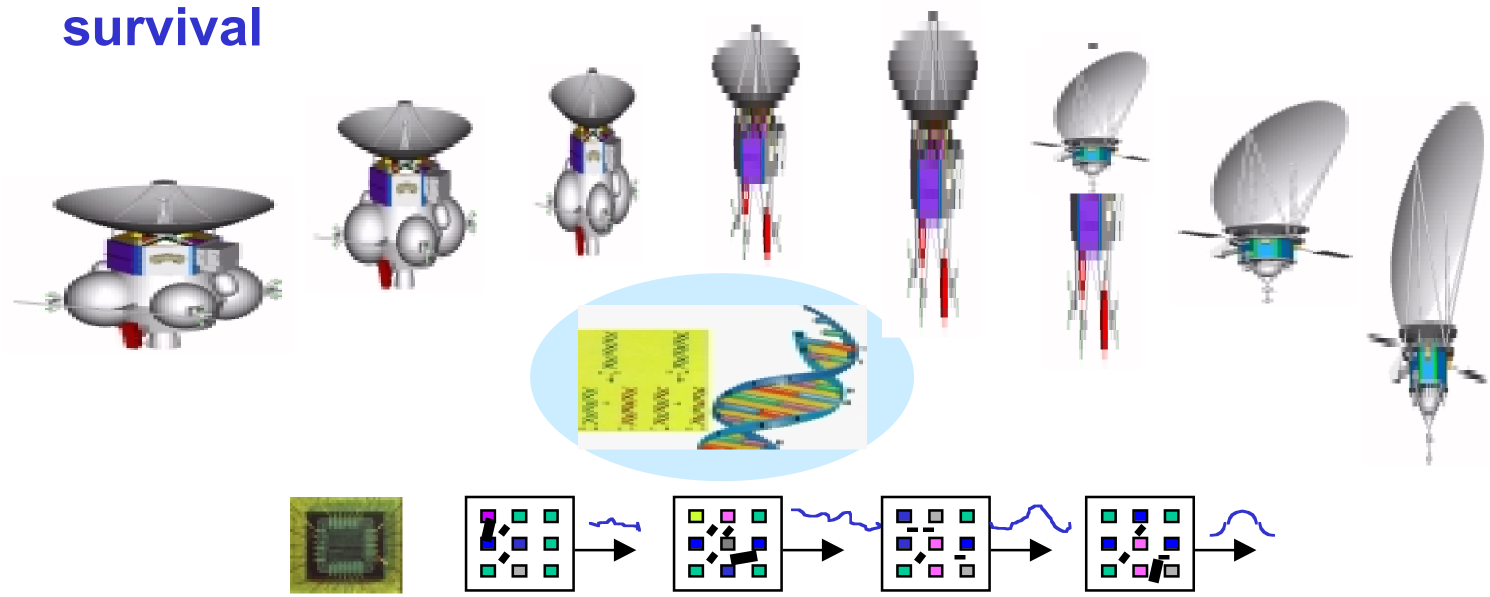
- Fleet, Swarm, Armada
- Some do not adapt, their unharmed resources are reused by survivors

In-situ reconfiguration of body shape to adapt to the task



# Evolvable Space Systems

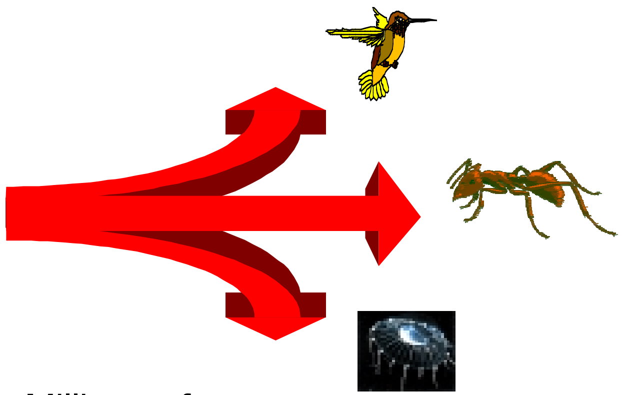
- Apply evolutionary algorithms to adaptively self-reconfigure space systems for long-life purposeful survival



- Evolution of Space Systems would include autonomous changes/reconfiguration of both software and hardware including sensors, avionics, structure...

# Inspiration and innovation

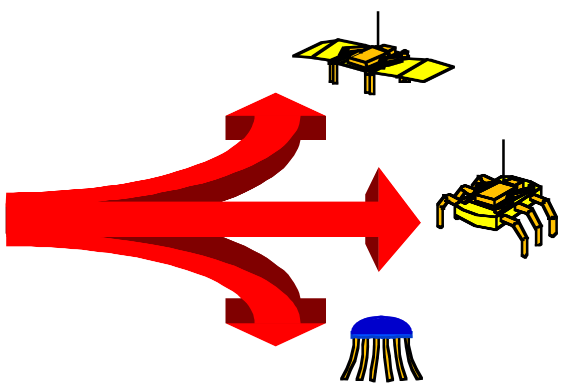
Evolution in nature has lead to species highly adapted to their environment - *adaptation ensured survival*.



Millions of years

The most fitted individuals survive becoming parents; children inherit parents characteristics, with some variations, may perform better, increasing the level of adaptation

The same evolutionary principles can be applied to machines

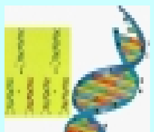


Accelerated evolution, ~ seconds for electronics

Potential designs and implementations compete; the best ones are slightly modified to search for even more suitable solutions

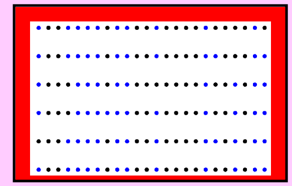
JPL

# Evolutionary Algorithms



Genetic search on a population of chromosomes
Reproduction of individuals with high fitness

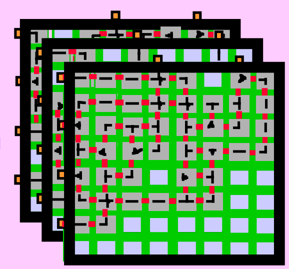
Chromosomes

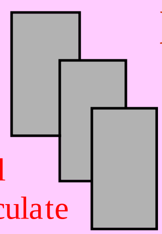


In essence the algorithm would:

- select the best (fittest) designs (or strategies) from a population of attempted spectrum of designs, and
- reproduce them with some variation in the new generation of designs.
- Iterate continuously until the performance goal is reached.

Population of Solutions (e.g. Circuits)

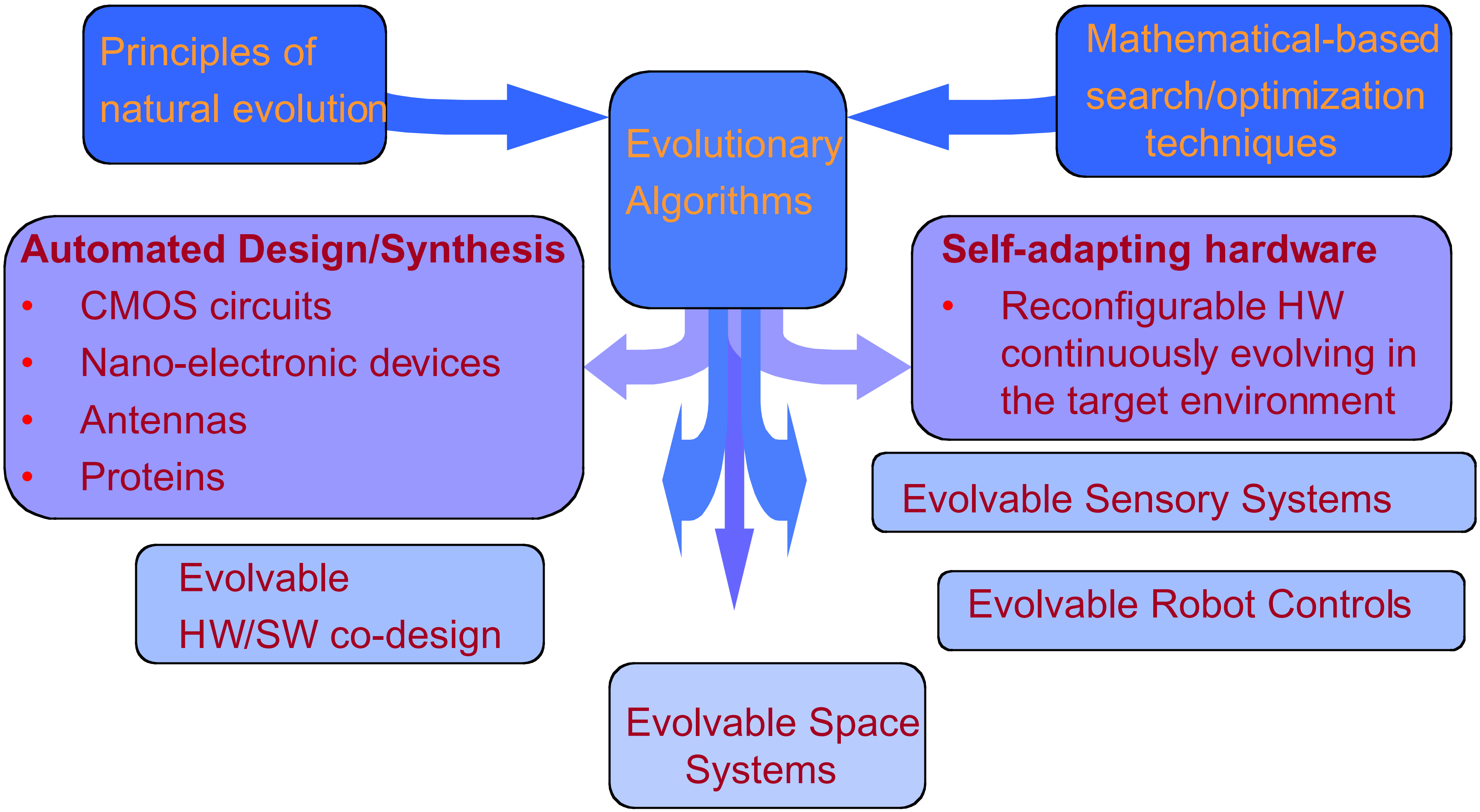




Target

Measure individual responses and calculate their fitness

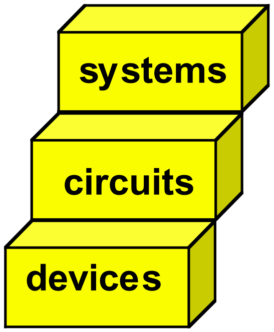
# Evolware


Principles of natural evolution
Mathematical-based search/optimization techniques
Evolutionary Algorithms
Automated Design/Synthesis
CMOS circuits
Nano-electronic devices
Antennas
Proteins
Self-adapting hardware
Reconfigurable HW continuously evolving in the target environment
Evolvable Sensory Systems
Evolvable HW/SW co-design
Evolvable Robot Controls
Evolvable Space Systems

# Evolution = Optimization

Artificial evolution is an optimization process. The optimization can be made for one or more characteristics simultaneously - e.g. function, cost, power, survivability, size

Optimization at design phase
- before mission -




Example:
• Evolve very small components
• Evolve multi-functional/reconfigurable components
• Evolve robust/fault-tolerant/self-healing components
• Evolve optimal designs at system level

Optimization during mission:
(optimal) adaptation to new situations, changes in requirements

Example
• Evolve new functions, unforeseen at launch
• Evolve for in-situ adaptation
• Evolve to self-heal

# “Genetically Engineered” Nanoelectronic Devices

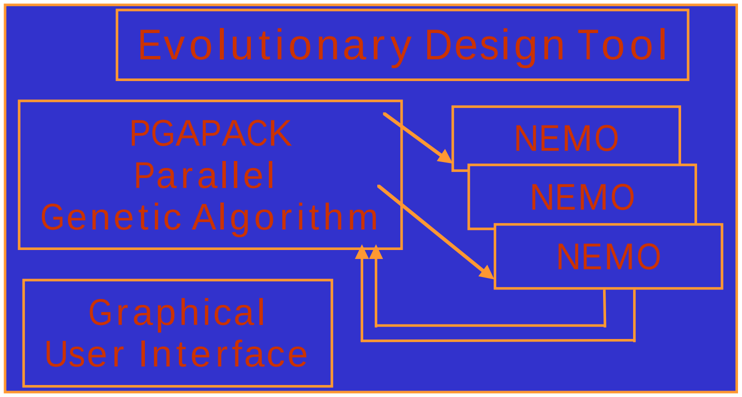
Gerhard Klimeck(385), Adrian Stoica (344)

## Objective:
- Automated device synthesis and analysis using genetic algorithms.

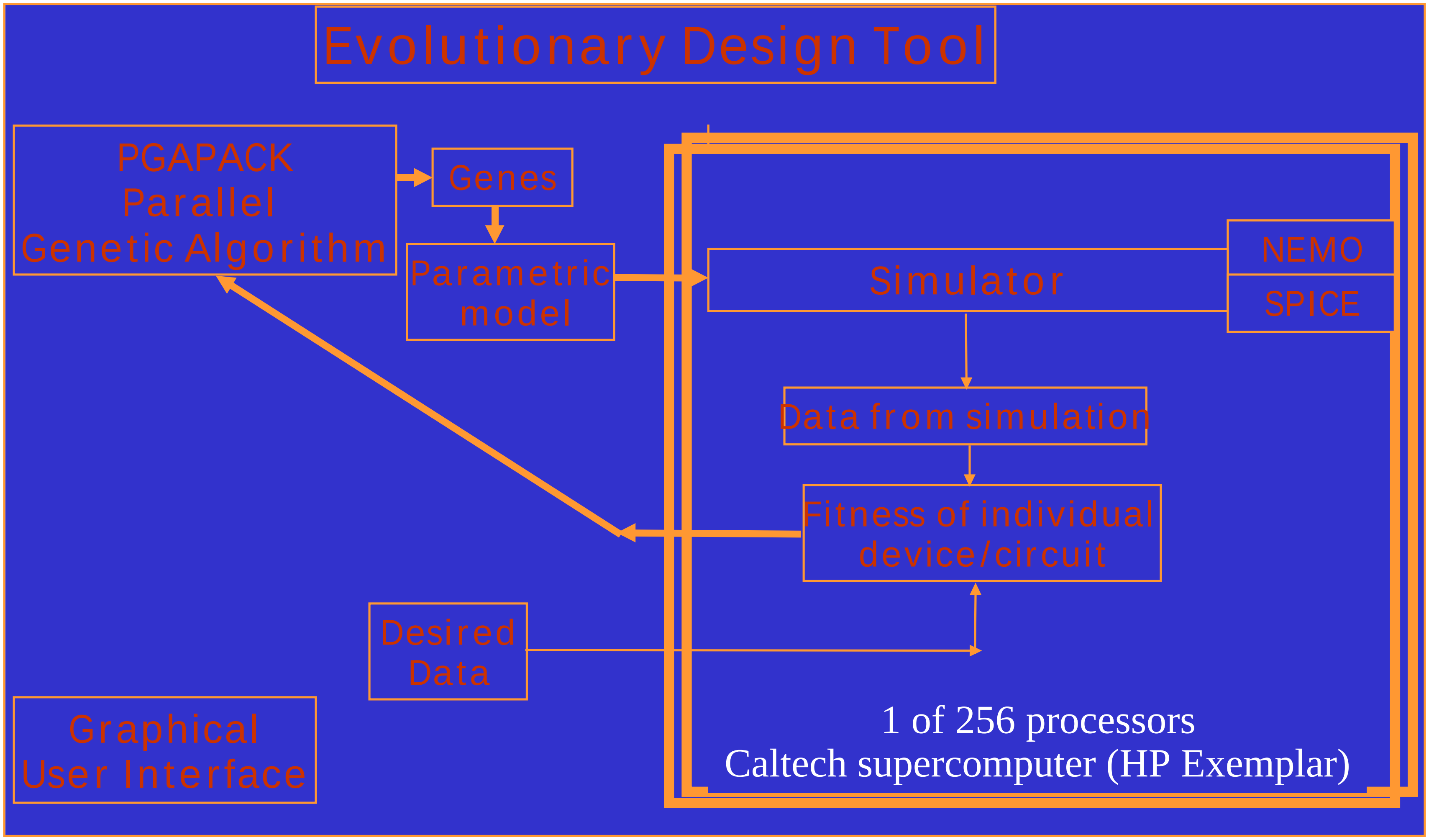
## Justification:
- Empirical Design (usual process) is sub-optimal. Complete design space search is unfeasible.
  => Develop automated design tools.

## Impact:
- Rapid nanotechnology device synthesis and development.
- Generation of novel devices.

## Approach:
- Augment recently developed advanced NanoElectronic MOdeling (NEMO) tool analyze individual structures in parallel.
- Augment parallel genetic algorithm package (PGApack) to optimize and select desired structures in NEMO.
- Develop graphical user interface to enable access to set of evolutionary quantum device design models.



# Simulated evolution in a parallel implementation

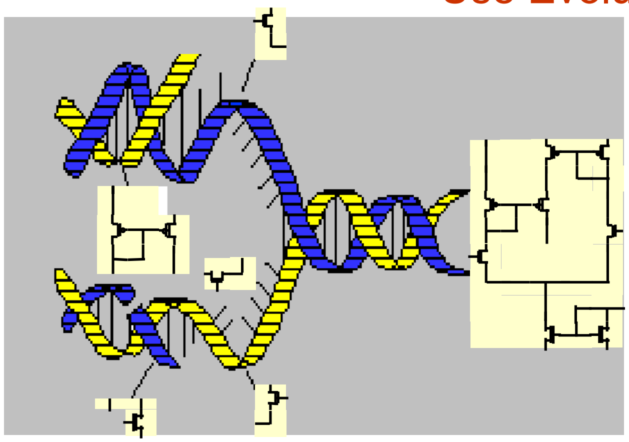


# Evolvable Electronic Circuits

**Objective:** Automated circuit design/synthesis/optimization using evolutionary algorithms.

**Justification:**
- Empirical Design is sub-optimal. Complete design space search is unfeasible.
- Rapid design
- Generation of novel circuits

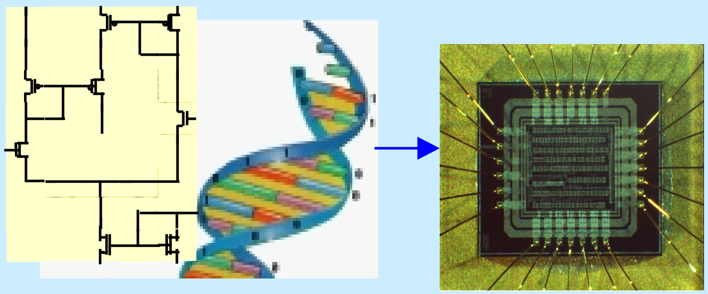
**Approach:**
- Find appropriate genotype to phenotype mappings
- Use Evolutionary Design Tool with SPICE



- Multi-criteria optimization (power, speed, etc.)
- Automated design in space, without human designer intervention
- Validation for synthesis of new circuits directly in reconfigurable hardware

# Evolvable Electronic Circuits (II)

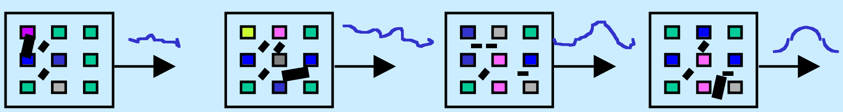
**Objective**: Develop microelectronics chips capable of self-reconfiguration for adaptation to the environment



Genetic Algorithm Microelectronics

**Approach:**

- **Use reconfigurable cells**
- **Achieve self-organization by reassigning cell function & connections between cells**
- **Use powerful parallel searches (e.g. genetic algorithms) directly in hardware, to evolve chip architecture**



**Payoff: Achieve high autonomy on-board spacecraft**

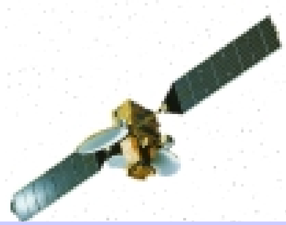
- **Maintain functionality under changes in operating conditions**
- **Provide new functions, not anticipated on ground**

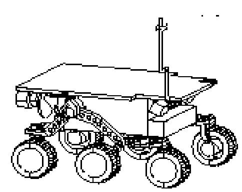
# How Evolvable Space Systems would Revolutionize NASA Missions

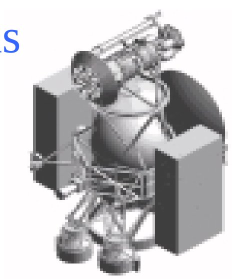
- Long life, survivable, self-healing space systems
  - would allow long duration/far out missions
  - would harness required power and other resources from environment

- Would enable *evolvable missions* capturing science/exploration opportunities in real time

- Space explorer
  - would produce knowledge from acquired data
  - would use the knowledge to mission refocus/replanning
  - would be able to create new functions, unforeseen before launch
  - would be able to learn on-the-fly to best deal with changing conditions







Evolvable system technology:
adaptive platform for space systems in a large variety of missions

## Technical Challenges

- Efficient representations, architectures, algorithms
  - Identify *DNA-equivalent* for a space system for it to become reconfigurable, evolvable, self-healing, capable of reconstructing after damage..
  - How to empower the system to *direct and execute* the evolutionary process
  - Define *fitness functions* for evolvability
- Revolutionary advances in materials, components, and structures for inherent evolvability
- Breakthrough in validation techniques
- System level perspective

# Technology Goals

**10 years..**

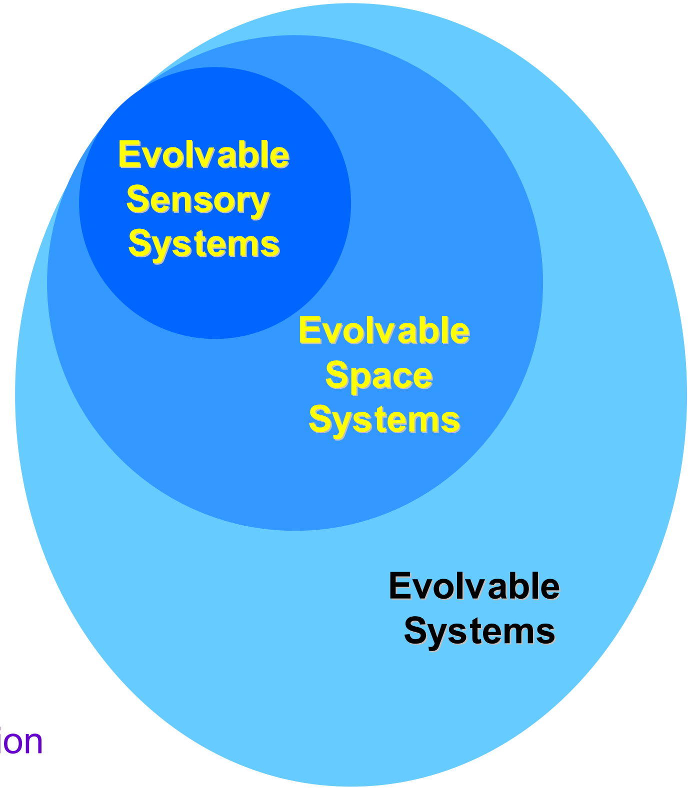
**Evolvable Sensory Systems for Space Explorers**

- Evolution of electronic circuits directly on-chip, performing a flight-relevant function (e.g. data compression)
- Intelligent adaptation of a science instrument
- Intelligent sequencing of instruments, adapt individual instruments
- Adaptive/Intelligent space sensory systems

**15-20 years..**

**Evolvable Space Systems**

- Adaptation of materials, structural/mechanical components, sub-assemblies
- Self-healing, automatic mission planning from high-level mission goals
- Long life, inherently survivable space systems



# The last slide: in-situ adaptation...